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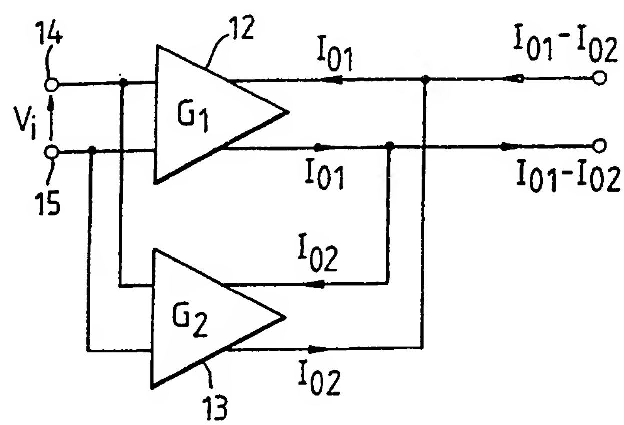
(54) **Transconductance amplifier**

(57) A transconductance amplifier device comprises two separate transconductance amplifiers 12, 13, the respective transconductances of which act in opposite senses, such that non-linearities in these transconductances tend to cancel to produce for the device an overall transconductance which is more linear than either of the individual transconductances. The amplifiers may be emitter coupled pairs (Fig 7).

Fig. 5.



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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig.1.

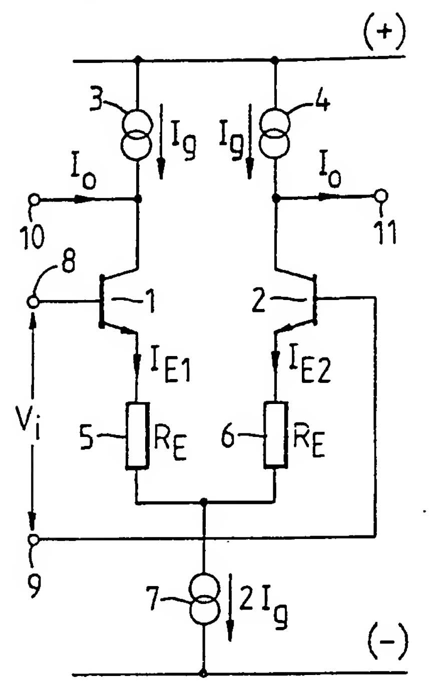


Fig.2.

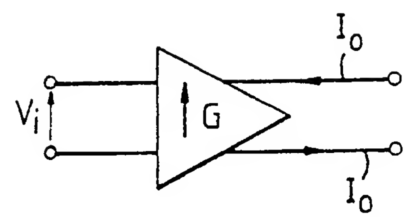


Fig.4.

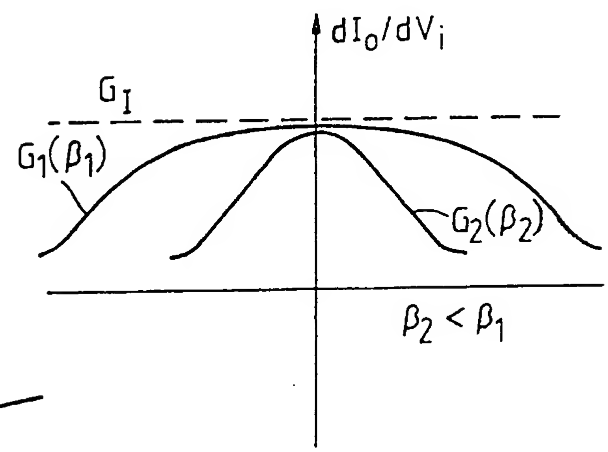


Fig.3.

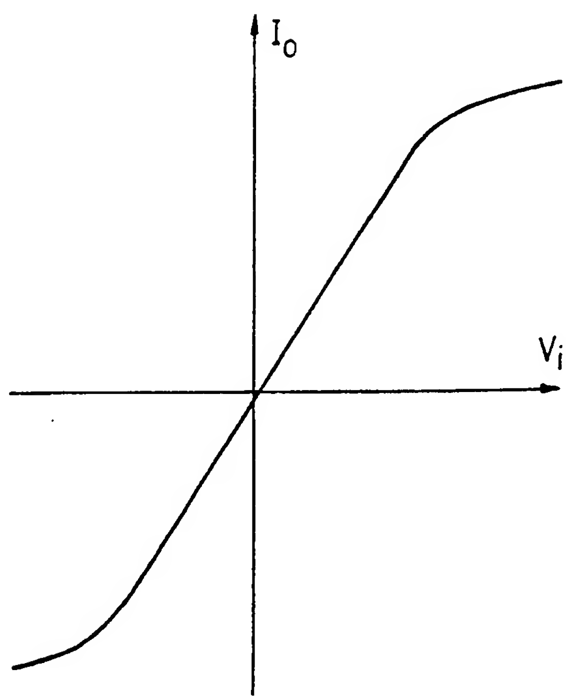


Fig. 5.

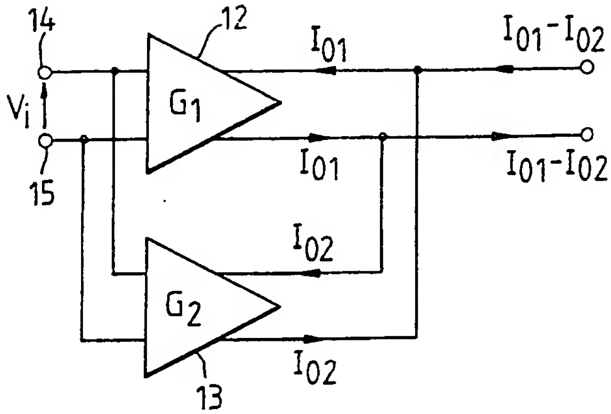
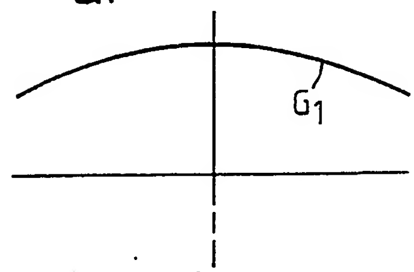
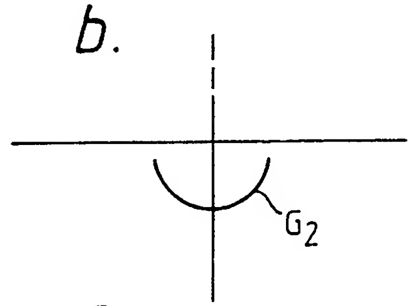


Fig. 6.

a.



b.



c.

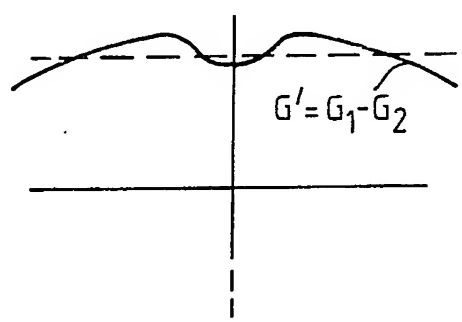


Fig. 7.

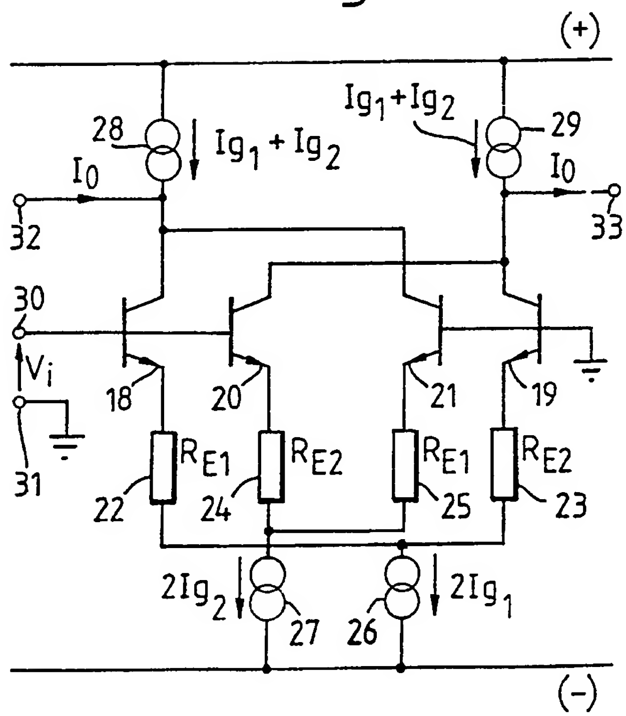


Fig. 8.

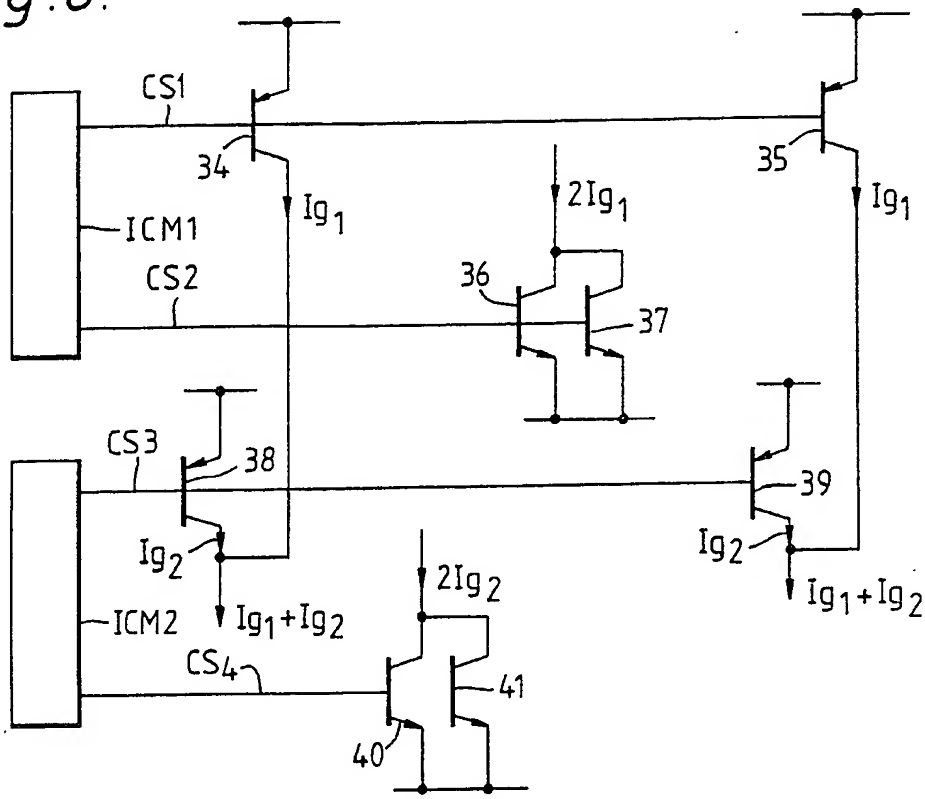


Fig. 9.

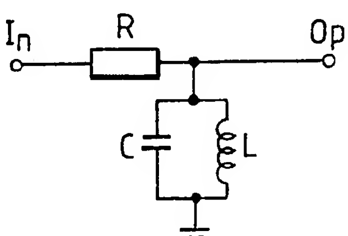


Fig. 10.

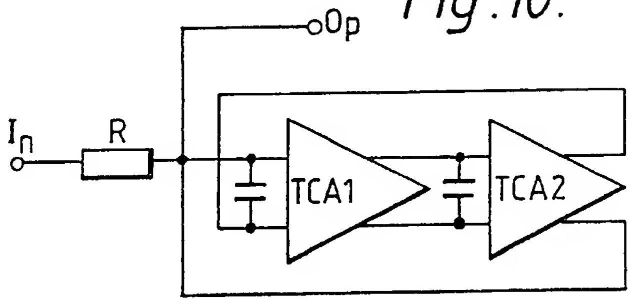
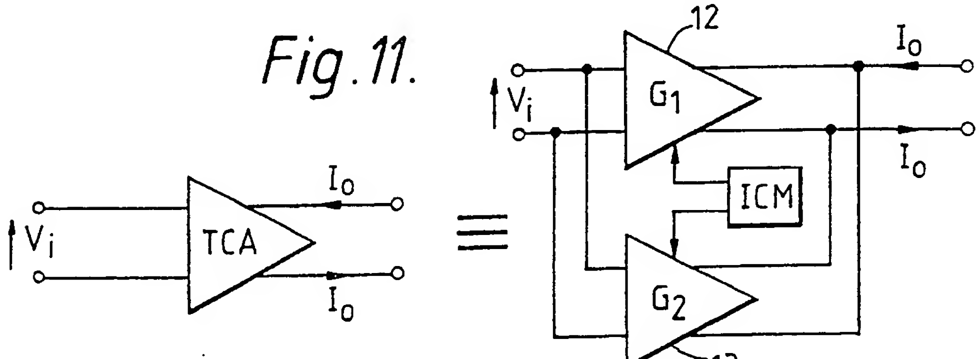


Fig. 11.



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DESCRIPTION

TRANSCONDUCTANCE AMPLIFIER

This invention relates to transconductance amplifiers, that is voltage-to-current amplifiers which produce an output current as a function of an input voltage.

For an ideal transconductance amplifier, the value of output current I_o in response to an input voltage V_i is given by the equation:-

$$I_o = GV_i \qquad (1)$$

where G is the transconductance of the amplifier.

However, the transfer characteristics of all practical amplifiers have a measure of non-linearity, and for a practical transconductance amplifier the output current I_o is related to the input voltage V_i by the equation:-

$$I_o=A_o+A_1V_i+A_2V_i^2+A_3V_i^3+ \ldots \qquad (2)$$

where A_1, A_2, A_3 etc are constants, A_o is a dc component, and only A_1=G.

This non-linearity in the transfer characteristic can cause distortion in the output waveform, in that it introduces into the output signal frequency components that are not present in the input signal. The reason for this is the multiplication of the different frequency components of the input signal by the V_i^n terms in equation (2).

For example, if the input voltage signal is a sinusoidal single frequency component f, then the output current signal will have a waveform containing the same fundamental frequency f, but the non-linearity in the transfer characteristic of the amplifier will cause harmonics of frequencies 2f, 3f, etc., that is, harmonic distortion will be present. The amount of harmonic distortion will be dependent on the input signal amplitude. The acceptable overall level of distortion in the output signal will be dependent on the particular application of the transconductance amplifier. For example, in video applications, harmonic distortion of the order of 1% (-40dB) of the fundamental frequency component might be taken as a limit. This limit will determine the maximum input signal

amplitude that would be permitted for a given transconductance amplifier.

It is an object of the present invention to provide means for improving the linearity of the transfer characteristic of transconductance amplifier devices.

According to the invention, there is provided a transconductance amplifier device comprising two separate transconductance amplifiers, the respective transconductances of which act in opposite senses, such that non-linearities in these individual transconductances tend to cancel to produce for the device an overall transconductance which is more linear than either of the individual transconductances.

In one aspect of the invention, the transconductances of the two separate amplifiers are both controllable. In another aspect of the invention, only one of the individual transconductances of the two separate amplifiers is controllable, the other being fixed. In each aspect, it is preferable for one transconductance to be smaller than the other so as not to reduce the dynamic tuning range of the device to an unacceptable extent.

In the first aspect of the invention an improvement is attained in that the resultant transconductance of the device is more linear for a larger input voltage swing than either of the individual transconductances. In the second aspect of the invention, the sensitivity of the resultant transconductance is magnified relative to changes in the controllable tranconductance. Thus, the resultant transconductance is more controllable than the individual fixed transconductance.

A transconductance amplifier device according to the invention can be formed from two balanced transconductance amplifiers each comprising two transistors connected in a long-tailed pair configuration between supply lines and having separate current sources in their collector circuits and a common current source in their common emitter circuits, the current through at least one of these transistors being controlled by control of the associated current source to determine the overall transconductance of the

amplifier device.

The various current sources are suitably provided as transistors, the conductive states of which are controllable by control signals applied to their bases from input control means.

In order that the invention may be more fully understood reference will now be made by way of example to the accompanying drawings, of which:-

Figure 1 is a circuit of a known transconductance amplifier;

Figure 2 represents an equivalence diagram for the amplifier of Figure 1;

Figures 3 and 4 show different parameters for the amplifier of Figure 1;

Figure 5 shows an equivalence diagram of a transconductor amplifier device according to the invention;

Figure 6 shows the transconductance characteristics for the two transconductance amplfiers used in the device of Figure 5;

Figure 7 is a circuit of the device according to the invention;

Figure 8 is a control circuit for the device of Figure 7;

Figure 9 is a circuit of a simple notch filter; and

Figures 10 and 11 illustrate the use of devices according to the invention in the implementation of the filter of Figure 9.

Referring to the drawings, the circuit of the transconductance amplifier shown in Figure 1 is that of a balanced transconductor and comprises two transistors 1 and 2 which are connected in a long-tailed pair configuration between supply lines (+), (-). Respective current sources 3 and 4 are connected in the collector circuits of the two transistors 1 and 2 and respective resistances 5 and 6 are connected in their emitter circuits. A further, common, current source 7 is connected between the ends of the resistances 5 and 6 remote from the transistor emitters and the supply line (-).

As indicated in Figure 1, each of the current sources 3 and 4 provides a current I_g and the current source 7 provides a current $2I_g$. The resistances 5 and 6 each have a value R_E. The two

transistors 1 and 2 have respective dynamic emitter resistances r_{E1} and r_{E2} which vary with their emitter currents I_{E1} and I_{E2}. An input voltage V_i is applied across input terminals 8 and 9 of the circuit, and output current I_o flows at output terminals 10 and 11. This transconductance amplifier is represented diagrammatically by the equivalence diagram shown in Figure 2.

The transconductance G of the amplifier is given by the equation:-

$$G=1/(2R_E+2r_E) \qquad (3)$$

For each of the transistors 1 and 2, the value of r_E is given by the equation:-

$$r_E= V_t/I_E \qquad (4)$$

where V_t is the transistor base/emitter voltage.

By controlling the dc current I_g in one or both of the transistors 1 and 2 the transconductance G of the circuit can be altered.

Non-linearities in the input voltage V_i/output current I_o characteristic of the circuit will be present. Figure 3 shows a typical example of this characteristic. These non-linearities result largely from changes in the emitter resistances r_{E1} and r_{E2} as the output current I_o changes, that is:-

$$r_{E1} = V_t/(I_o+I_g) \qquad (5)$$

$$r_{E2} = V_t/(I_g-I_o) \qquad (6)$$

Because the circuit is balanced (symmetrical), the values A_0, A_2, A_4 ... A_2n in equation (2) will be zero, so that:-

$$I_o = GV_i+A_3V_i^3+A_5V_i^5+ \ldots \qquad (7)$$

As shown in Figure 4, for an ideal transconductance amplifier, the transconductance G_I would be wholly linear for changes in output current versus input voltage i.e. dI_o/dV_i. However, in practice only transconductance curves such as G_1 and G_2 are attainable for different values of β which represents a measure of linearity for the amplifier. The value β can be represented by the equation:-

$$\beta = R_E/(R_E+r_E) \qquad (8)$$

where $r_E = r_{E1} = r_{E2}$, $(I_o=0)$.

When R_E is large compared to r_E (i.e. $\beta \simeq 1$), the non-linear part r_E in the amplifier has a negligible influence on the transconductance, and a relatively linear amplifier is realised. This gives low values for A_3 to A_5 in equation (7).

When r_E is large compared to R_E (i.e. $\beta \simeq 0$), the non-linear part r_E in the amplifier has a larger influence on the transconductance and a more non-linear amplifier is realised. This gives higher values of A_3 and A_5 in equation (7).

An important feature of the transconductance amplifier circuit shown in Figure 1 is that its transconductance is controllable. For each transistor, altering the current I_g changes the value of the associated emitter resistance r_E, and this changes the transconductance of the circuit. This feature is utilised to provide in accordance with the invention a transconductance amplifier device with improved linearity. The basic device is represented diagrammatically by the equivalence diagram of Figure 5. The device comprises two separate conductance amplifiers 12 and 13 which have respective transconductances G_1 and G_2. The two amplifiers share common input terminals to which the input voltage V_i is applied. The amplifier 12 produces an output current I_{o1} and the amplifier 13 produces an output current I_{o2}. These two currents are combined subtractively to produce a resultant output current $I_{o1}-I_{o2}$ at output terminals 16 and 17 of the device.

The amplifier 12 has the fairly linear transconductance curve G_1 shown in Figure 6a for a value β_1 and the amplifier 13 has the less linear transconductance curve $-G_2$ shown in Figure 6b for a value β_2. Subtracting the output current I_{o2} of the amplifier 13 from the output current I_{o1} of the amplifier 12 gives a resulant transconductance value G^1 as shown in Figure 6c which is more linear than can be obtained with an equivalent single transconductance amplifier.

More specifically:-

$$G' = G_1 - G_2 \qquad (9)$$

where $G_2 < G_1$, and $\beta_2 < \beta_1$

For the amplifier 12:-

$$I_{o1} = G_1V_i+A_3V_i^3+A_5V_i^5+ \ldots \quad (10)$$

For the amplifier 13:-

$$I_{o2} = G_2V_i+B_3V_i^3+B_5V_i^5+ \ldots \quad (11)$$

where B_3,B_5, etc., are equivalent constants to A_3, A_5, etc.

Therefore:-

$$I_o=I_{o1}-I_{o2}$$
$$= (G_1-G_2)V_i+(A_3-B_3)V_i^3 + (A_5-B_5)V_i^5+ \ldots \quad (12)$$

where the first term defines the linear part of the output current and the subsequent terms define the non-linear part.

It can be seen from the foregoing that the non-linearities of G_1 and G_2 act in opposite senses. G_2 is more non-linear, but since G_2 is smaller than G_1, the non-linearity of G_2 can be made to be approximately equal, but of opposite polarity, to the non-linearity of G_1. As a conseqeunce, distortion produced by one transconductance amplifier is approximately cancelled by the distortion produced by the other transconductance amplifier. The resulting transconductance G^1 of the composite transconductance amplifier device is therefore more linear for a larger input signal voltage than is possible for an equivalent single transconductance amplifier.

It is mentioned that the composite transconductance amplifier device may not be as controllable as an equivalent single transconductance amplifier, because the smaller less linear transconductance G_2 may change further in the opposite sense than the transconductance G_1, thereby over-compensating the correction to improve linearity. Reducing both β_1 and β_2 can restore the controllability of the device, while still achieving improvements in linearity.

In the foregoing description with reference to Figures 4, 5 and 6 of the transconductance amplifier device, it has been assumed that both the respective conductances G_1 and G_2 of the two amplifiers 12 and 13 are controllable. However, it is also with the scope of the present invention for only one of these two transconductances to be controllable, the other being fixed.

Improved linearity of the overall transconductance can still be achieved in this situation, as will now be explained. As before, the overall transconductance G^1 is composed of the two transconductances $G_1(\beta_1)$ and $G_2(\beta_2)$. In this instance:-

$$G_2 = k\ G_1 \qquad (13)$$

where k is a constant less than unity.

$$\text{Also, } B_1 >= \beta_2 \qquad (14)$$

$$\text{and } G^1 = G_1 - G_2 \qquad (15)$$

The ability to control G_1 is used, but G_2 has a fixed value of β_2.

Considering the sensitivity of G^1 to changes in G_1 and G_2 gives:-

$$\frac{dG^1}{G^1} = \frac{dG_1 - dG_2}{G_1 - G_2} \qquad (16)$$

Since G_2 is fixed, $dG_2 = 0$. (17)

$$\text{Therefore, } \frac{dG^1}{G^1} = \frac{dG_1}{G_1 - G_2} \qquad (18)$$

$$\text{But, } G_2 = kG_1 \qquad (19)$$

$$\text{So} \quad \frac{dG^1}{G^1} = \frac{dG_1}{G_1\ (1-k)} \qquad (20)$$

For example, if k = 0.5, then a 10% change in G_1 gives a 20% change in G^1.

As a consequence, the composite transconductance amplifier device with the overall transconductance G^1 is more sensitive to changes in G_1 by a factor $1/(1-k)$ than a single transconductance amplifier with the transconductance G_1. Therefore the composite device has a wider control range than the single amplifier. Changing β_1 by increasing I_g and G_1 for the controllable amplifier, whilst retaining the relationship $\beta_1 > \beta_2$, will always provide an overall transconductance G^1 that is at least as linear as G_2. For this latter situation to achieve improved linearity of the overall transconductance, the extra tuning range can be sacrificed by designing the composite amplifier device with increased β_1 and β_2, so as to give an overall improvement in linearity over an equivalent single transconductance amplifier, but retaining equal

control over the transconductance.

The overall circuit of a transconductance amplifier device according to the invention is shown in Figure 7. This circuit comprises a first pair of transistors 18 and 19 of a first transconductance amplifier and a second pair of transistors 20 and 21 of a second transconductance amplifier. Both pairs of transistors are connected in a respective long-tailed pair configuration between supply lines (+1), (-). The two transistors 18 and 19 have respective resistances 22 and 23 of value R_{E1} connected in their emitter circuits and, similarly, the two transistors 20 and 21 have respective resistances 24 and 25 of value R_{E2} connected in their emitter circuits. A common current source 26 is connected between the supply line (-) and the side of the resistances 22 and 23 remote from the transistor emitters. Likewise, a common current source 27 is connected between the supply line (-) and the side of the resistances 24 and 25 remote from the transistor emitters. The two current sources provide currents $2I_{g1}$ and $2I_{g2}$ respectively. The collectors of transistors 18 and 21 are connected in common to a current source 28 and the collectors of transistors 19 and 20 are connected to a current source 29. Each of the current sources 28 and 29 supplies a current $I_{g1}+ I_{g2}$. Input terminals 30 and 31 receive an input signal voltage Vi, and an output current I_o is produced at output terminals 32 and 33. The control of the transconductance of one or of both the transconductance amplifiers is exercised through the current sources 28 and 29, that is the dc current I_{g1} and/or I_{g2} is controlled externally.

The control circuit shown in Figure 8 gives an example of how this control may be exercised. This control circuit comprises a first section, comprising transistors 34, 35, 36 and 37, which is controlled by control signals CS1 and CS2 from a first input control means ICM1. The control signal CS1 acts on the bases of the transistors 34 and 35 to control their conduction. The emitter currents through these transistors each form the current I_g1. The control signal CS2 acts on the base of the transistors 36 and 37 to

control their conduction. Their combined collector currents form the current $2I_{g}1$. The control circuit also includes a section which similarly comprises transistors 38, 39, 40 and 49, the conductive states of which are determined by control signals Cs3 and CS4 from a second input control means ICM2. The transistors 38 and 39 each provide a current I_{g2} and the transistors 40 and 41 provide a combined current $2I_{g2}$.

The transistors 34 and 38 together form the current source 28 in Figure 7 and provide the current $I_{g1} + I_{g2}$. The transistors 35 and 39 together form the current source 29 and also provide the current $I_{g1} + I_{g2}$. The two transistors 36 and 37 form the current source 26 and provide the current $2I_{g1}$ and the two transistors 40 and 41 form the current source 27 and provide the current $2I_{g2}$.

The input control means ICM1 and ICM2 would be of a form appropriate to the application of a transconductance amplifier device according to the invention. One possible application as a gyrator notch filter will now be considered.

Figure 9 shows a fundamental filter circuit comprising a resistance R and capacitance C and an inductance L connected and having an input In and an output Op. The equivalent gyrator circuit is shown in Figure 10, where the capacitance C and the inductance L have been replaced by two transconductance amplifiers TCA1 and TCA2 connected in cascade. As shown in Figure 11, each of the transconductance amplifiers TCA1 and TCA2 can be implemented by a transconductance amplifier device TCA according to the invention, with an associated current control circuit ICM.

This application of a transconductance amplifier device according to the invention in a gyrator based analogue filter can be implemented on an integrated circuit incorporating electrically noisy digital circuitry. This becomes possible because the linearising of the two transconductance of the separate amplifiers of the device does not interfere with the frequency response of the device, nor does it influence its stability.

From reading the present disclosure, other modifications will be apparent to persons skilled in the art. Such modifications may

involve other features which are already known per se of and which may be used instead of or in addition to features already described herein. Although claims have been formulated in this application to particular combinations of features, it should be understood that the scope of the disclosure of the present application also includes any novel feature or any novel combination of features disclosed herein either explicitly or implicitly or any generalisation thereof, whether or not it relates to the same invention as presently claimed in any claim and whether or not it mitigates any or all of the same technical problems as does the present invention. The applicants hereby give notice that new claims may be formulated to such features and/or combinations of such features during the prosecution of the present application or of any further application derived therefrom.

CLAIM(S)

1. A transconductance amplifier device comprising two separate transconductance amplifiers the respective transconductances of which act in opposite senses, such that non-linearities in these individual transconductances tend to cancel to produce for the device an overall transconductance which is more linear than either of the individual transconductances.

2. A transconductance amplifier device as claimed in Claim 1, characterised in that the individual transconductances of the two separate amplifiers are both controllable.

3. A transconductance amplifier device as claimed in Claim 1, characterised in that only one of the individual transconductances of the two separate amplifiers is controllable, the other being fixed.

4. A transconductance amplifier device as claimed in any preceding claim, characterised in that one of the individual transconductances is smaller than the other.

5. A transconductance amplifier device as claimed in any preceding claim, characterised in that each of said separate amplifiers is a balanced transconductance amplifier comprising two transistors connected in a long-tailed pair configuration between supply lines and having separate current sources in their collector circuits and a common current source in their common emitter circuits, the current through at least one of these transistors being controllable by control of the associated current source to determine the overall transconductance of the amplifier device.

6. A transconductance amplifier device as claimed in Claim 5, characterised in that said current sources are transistors, the conductive states of which are controllable by control signals applied to their bases from input control means.

7. A transconductance amplifier device, substantially as hereinbefore described with reference to Figures 1 to 7 of the accompanying drawings.

8. A transconductance amplifier device as claimed in Claim 7, having an associated current control circuit, substantially as

hereinbefore described with reference to Figure 8 of the accompanying drawings.

9. A gyrator notch filter implemented as two devices and an associated current control circuit as claimed in Claims 7 and 8, substantially as hereinbefore described with reference to Figures 9 to 11 of the accompanying drawings.

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